HapSeat: Producing Motion Sensation with Multiple Force-feedback Devices Embedded in a Seat

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ABSTRACT

We introduce a novel way of simulating sensations of motion which does not require an expensive and cumbersome motion platform. Multiple force-feedbacks are applied to the seated user's body to generate a sensation of motion experiencing passive navigation. A set of force-feedback devices such as mobile armrests or headrests are arranged around a seat so that they can apply forces to the user. We have dubbed this new approach *HapSeat*. A proof of concept has been designed which uses three low-cost force-feedback devices, and two control models have been implemented. Results from the first user study suggest that subjective sensations of motion are reliably generated using either model. Our results pave the way to a novel device to generate consumer motion effects based on our prototype.

Categories and Subject Descriptors

H5.2 [**Information interfaces and presentation**]: User Interfaces. - Haptic I/O.

General Terms

Design, Experimentation

Keywords

sensation of motion, force-feedback, haptic seat, audiovisual experience

1. INTRODUCTION

Motion simulation is usually provided by a motion platform [8]. Typically the user's whole body is moved to generate various sensations such as accelerating, falling or passing over bumps. While these devices generate a realistic sensation of motion with 6DoF, they are not designed for domestic settings and they are too expensive for the mass consumer market. Immersive experiences with motion effects are thus currently limited to amusement parks or "4D Cinemas".

In this article we present the *HapSeat*, a novel approach for producing motion sensations in a consumer settings using multiple force-feedback devices embedded in a seat. Three low-cost actuators which simulate 6DoF effects of motion are used. The motion effect is generated by adjuncts to the structure of the chair rather than moving the whole chair. A proof-of-concept prototype has been designed and constructed, which uses actuators held by an armchair-shaped structure (see figure 1). Two models to control the device has been implemented: a *Physical Model* which computes forces supposed to be felt during a movement, and a *Geometrical Model* which modifies the structure to match the position and posture that characterize a movement.

A user study was conducted to assess this approach. Participants reported a sensation of motion. When applied to a passive navigation simulation in a real or virtual environment, our results show that the *HapSeat* increases the quality of the user experience. We considered four factors

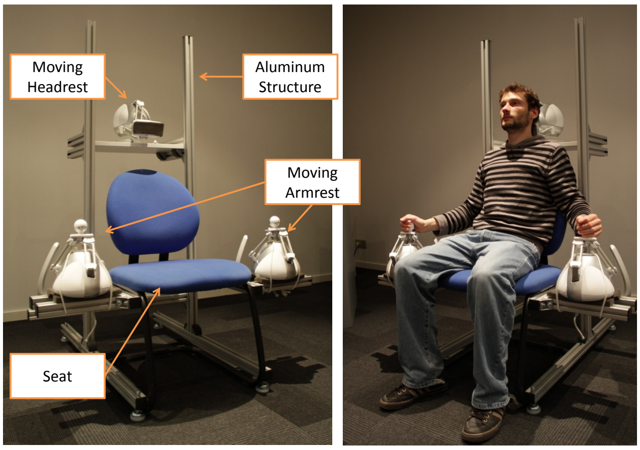

Figure 1: Prototype of the HapSeat. Left: seat structure with 3 force-feedback devices. Right: the system in use.

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in the measurement of the QoE: realism (of the simulation), sensory (involvement of the sense of touch), comfort and satisfaction.
In this paper we first review the literature on human motion perception and motion simulators (section 2). Then the *HapSeat* is introduced in section 3 while section 4 details the proof of concept. The user study is discussed in section 5. Finally a conclusion and perspectives are provided in section 6.

2. RELATED WORK

2.1 Human motion perception

The perception of motion is a complex sensation resulting from the integration of multiple perceptive inputs from different systems: visual, auditory, vestibular and kinesthetic [1, 4]. The visual system contributes to this perception by providing an estimation of distances between the body and landmarks. A displacement of the body will modify these distances and add the perception of self-motion. Moving visual cues can often trigger a sensation of self-motion even though the viewer is stationary [10]. This illusion is called vection. The auditory system may also contribute to this perception by locating the body relative to "acoustic" landmarks [15].
But the main contributor to the perception of motion is the vestibular system. Located in the inner ear, this organ is composed of three orthogonally-oriented semi-circular canals and two otolith organs. The canals allow rotational movements to be detected while otolith organs contribute to the perception of linear accelerations.
Finally, it is interesting to note that haptic cues provided by the kinesthetic system also influence the sensation of motion. The kinesthetic system provides information about limb positions. When an elevator goes up, one feels the motion thanks to the proprioreceptive receptors in joints and muscles of the legs. The tactile sense also provides information about motion: internal receptors detect movements of visceral organs and act as accelerometers. These visceral graviceptors are especially to be be found in the region of the kidney. The somatosensory system indicates the direction of gravity through pressure patterns all over and inside the body [14].

2.2 Motion simulators

Motion simulators are well-known devices designed to make the user feel motion. They are intensively used in driving or flight simulators for training purposes. Most are based on a Stewart's platform [3], a 6 Degrees of Freedom (DoF) platform driven by 6 hydraulic cylinders. A motion simulator is basically a seat attached to this kind of platform. While the user navigates the virtual environment, the seat moves to generate a sensation of motion. These systems are often used in virtual reality rooms or 4D cinemas but few are designed for the end-user consumer.
To the best of our knowledge, the D-Box company[1] is one of the few actors in this market, having developed an armchair placed on four actuators that is suitable for an end-user's living-rooms. This seat generates 3DoF motion effects (pitch, roll and heave) for movie viewing and consumer applications. Despite this attempt to succeed in the consumer environment, this chair remains expensive and limited to 3DoF motion effects.
The sensation of motion can also be induced in a less invasive way by force-feedback devices that simulate the kinesthetic system. Ouarti et al. applied a force to users' hands as they watched an optic flow stimulus [9]. The system was expected to generate an illusion of motion with force-feedback: when the interface pulled the user's hand, the user experienced a sensation of forward motion. Similarly, Danieau et al. used a 3DoF force-feedback device to induce the sensation of global movement in a video [2]. This system was designed to enhance audiovisual content as a cheaper alternative to motion platforms, but the movement simulated was limited to 3DoF (translations only).
The use of haptic illusions to enhance the audiovisual experience has also been explored by Israr et al., who designed a chair with several vibration devices embedded at different locations [5]. Actuators in the chair were activated in such a way that the user felt a continuous stimulus. Though no effect of motion was claimed in this study, Riecke et al. have showed that vibrotactile feedback may generate a vection effect by improving the realism of the simulation [11].
To sum up, there remains an important gap between haptic devices which do not, or only partially simulate, a sensation of motion, and complex simulators which are efficient in conveying motion but remain expensive and not well adapted to the consumer environment. We propose our *HapSeat* as a solution to fill this gap.

3. HAPSEAT: A NOVEL APPROACH FOR SIMULATING 6DOF MOTION

We propose to enhance the experience of passive navigation in virtual or cinematic content using 6DoF motion effects generated by multiple force-feedback devices. Instead of moving the whole user's body as on motion platforms, only some parts of the body are stimulated. As described in section 2.1, the perception of motion results from the stimulation of various parts of the body (vestibular system, visceral organs, kinesthetic system). Our approach is built on the hypothesis that local haptic cues suffice to trigger a sensation of self-motion.
Previous work has shown that a 3DoF force-feedback applied to a user's hand may simulate a 3DoF motion effect in a video viewing context [2]. But the simulated motion is limited to 3DoF (translations). Using only one or two 3DoF force-feedback devices is not sufficient to invoke a 6DoF sensation of motion [13] (translations and rotations). Extending the approach to three 3DoF devices in order to apply three force-feedback stimulus to the user's body offers the possibility of simulating a global 6DoF effect of motion. A plane looping sensation could be simulated by pulling the head backward and lifting both arms simultaneously, while a car braking could be simulated by pushing both the head and hands forward.
This concept can be extended by stimulating other regions of the body, using 5x3DoF devices for instance.

4. PROOF OF CONCEPT

The prototype developed as a proof of concept relies on three actuators. Two stimulate the user's hands, while a third stimulates the head. As the vestibular system is located in the head, stimulating this part of the body should

[1] http://www.d-box.com

heighten the illusion of simulated motion.

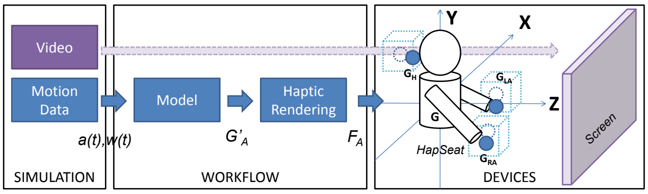

Figure 2: Simulating 6DoF motion with 3x3DoF force-feedback devices. While the three local devices are moving, the user is expected to feel a sensation of motion in relation to the visual content.

Figure 2 shows a schematic representation of the concept and offers an introduction to our notation. The motion description associated with a simulation is transmitted to a model at each instant t which computes the ideal position G'_A for each local actuator A. This position is then rendered by the haptic rendering algorithm as a force F_A. Each step of this workflow is detailed in this section.

4.1 Prototype of the HapSeat

An aluminum structure was designed to allow the positioning of the three actuators around an ordinary chair. The user passively rests his or her head and hands on each of the 3DoF actuators while watching a projection on a screen positioned in front of the chair (see figure 4). The head actuator is equipped with a block of foam for the user's comfort.
At rest (no rendered motions), the three actuators (H), (LA) and (RA) maintain the head, right arm and left arm of the user at the central positions G_H, G_{LA} and G_{RA} respectively. When the simulation starts, each actuator generates 3DoF forces on its respective body part within the limits of the cubic workspaces in figure 2.
Our current prototype uses three Novint Falcons[2] actuators. These devices are robust, relatively cheap and the forces generated are appropriate for safe movement of the user's head and hands.

4.2 Motion data

We focus on the case of a first person point-of-view simulation, whose intention is to mimic for the user the sensation of motion that the principal actor would have felt at the time of its recording. The audiovisual content is augmented with extra data describing the motion in terms of the linear acceleration $a(t)$ and the angular velocity $w(t)$. Let us define F_N as the navigation frame of the actor and F_B the frame associated with his body, centered on a point C (his chest for instance). The actor's motion is modeled as a rigid body motion described by two quantities $a(t) = [a(C \in F_B|F_N)]_{F_B} = \{a_x(t), a_y(t), a_z(t)\}^t$ (the gravity being removed [12]) and $w(t) = [w_{F_B/F_N}(t)]_{F_B} = \{w_x(t), w_y(t), w_z(t)\}^t$ (where the $[x]_F$ notation designates the vector x expressed in the frame F).
This kind of content can be easily produced by a video camera equipped with an inertial measurement unit. Danieau et al. used this setup to capture first-person point of view videos [2]. The capture device was attached to an actor's torso to record both his movement and a video of his field of view. Therefore $a(t)$ and $w(t)$ describe the motion of the actor.

[2] http://www.novint.com

4.3 Models for motion simulation

Each actuator (H, LA, RA) moves to create the feeling of 6DoF global motion modeled by the quantities $a(t)$ and $w(t)$ as if the motion of the main actor was mapped onto them. Two models to control the device were devised. The first model is based on a *Physical Model*. The related acceleration applied to some parts of the body of the actor (here the head, left hand and right hand) are derived from the parameters of the global motion, $a(t)$ and $w(t)$ and then reproduced on the user by the corresponding actuators. The second model, referred to as *Geometrical Model*, aims at reproducing the position and attitude of the main actor on the basis of a more metaphorical paradigm.

4.3.1 *Physical Model*

In this model the accelerations felt by the main actor at his head, P_H, and at his left and right shoulders, P_{LS} and P_{RS}, are computed through a rigid body approach, where the motions of the hands are considered equivalent to the movements of the shoulders. Knowing $a(t)$ and $w(t)$ at the origin of his body frame F_B, the accelerations of a new point P of the rigid body may be computed by the following mechanical relation (time derivation of the kinematic torsor):

$$[a(P \in F_B|F_N)]_{F_B} = a(t) + \frac{dw}{dt} \wedge \overrightarrow{GP} + w \wedge (w \wedge \overrightarrow{GP}) \quad (1)$$

The new position G'_A for an actuator A is the formulated in terms of displacement from its initial and central position G_A by:

$$\overrightarrow{G_A G'_A} = \begin{bmatrix} s_x & 0 & 0 \\ 0 & s_y & 0 \\ 0 & 0 & s_z \end{bmatrix} \quad (2a)$$

$$(a(t) + \frac{dw}{dt}(t) \wedge \overrightarrow{GP_A} + w(t) \wedge (w(t) \wedge \overrightarrow{GP_A})) \quad (2b)$$

where G'_A is the new application point at time t, and s_x, s_y, s_z are scaling factors which map the actual motions of the three actuators in their workspaces. Those scaling factors are computed so as to use the workspace of the actuator in an optimal way. This involves compromises between the use of the largest possible space, so as to have a larger amplitude in the final rendering, while avoiding any saturation. These scaling factors are computed is a preprocessing step that consists of finding the maximal amplitude of the acceleration rendered by the actuator.
In this context the new application points G'_H, G'_{LA} and G'_{RA} are computed from the intial points G_H, G_{LA} and G_{RA}, and $s_x = s_y = s_z$.

4.3.2 *Geometrical Model*

This second model aims to make the chair reproduce the position and posture of the moving actor during the simulation. Two kinds of motion will be rendered: linear accelerations and orientation changes. The linear acceleration rendering is simply performed by a simultaneous translation of each of the different local actuators along the 3D vector given by $a(t)$. The scene pose changes rendering is trickier. It makes the assumption that the rotation speed of the current scene, modeled by $w(t)$, may be rendered by

rotating the position of the three actuators around the center modeled by a point G located near the user's sternum (see figure 2) and with a 3D angle modeled by w. Then the faster the object is turning, the bigger the angle of rotation. Moreover, if the rotation stops (i.e. $w(t) = 0$), the actuators are at rest.
The new position G'_A of the actuator A for a rotation around G can be expressed:

$$\overrightarrow{GG'_A} = (R_x(w_x(t))R_y(w_y(t))R_z(w_z(t)))\overrightarrow{GG_A} \tag{3}$$

i.e.:

$$\overrightarrow{G_AG'_A} = \overrightarrow{GG'_A} - \overrightarrow{GG_A} \tag{4a}$$
$$= (R_x(w_x(t))R_y(w_y(t))R_z(w_z(t))) - I_3)\overrightarrow{GG_A} \tag{4b}$$

where R_x, R_y and R_z are the 3D rotation matrices around their respective X, Y and Z axes and I_3 is the identity matrix of R^3.
A complete 6DoF motion is a combination of linear accelerations and rotations. A function f is proposed to model the incorporation of both these types of information in our system. The proposed system has intentionally decoupled the linear motions from the rotational ones. This assumption is somewhat unrealistic from a mechanical point of view, but nevertheless makes sense in the context of passive navigation. If the motion to be rendered is a pure translation or a pure rotation, this decoupling is not a restriction. The difficulty arises when the motion to be rendered is a combination of translation and rotation. We make the assumption that a user would unconsciously expect to feel the dominant motion in the scene more strongly.
Then, if G_A represents the new position of the actuator A at time t and G_A its initial position, we have:

$$\overrightarrow{G_AG'_A} = f(\begin{bmatrix} s_x & 0 & 0 \\ 0 & s_y & 0 \\ 0 & 0 & s_z \end{bmatrix} a(t), \tag{5a}$$
$$(R_x(m_xw_x(t))R_y(m_yw_y(t))R_z(m_zw_z(t)) - I_3)\overrightarrow{GG_A}) \tag{5b}$$

with

$$f(B,C) = \frac{\|\vec{B}\|B + \|\vec{C}\|C}{\|\vec{B}\| + \|\vec{C}\|} \tag{6}$$

From this equation, the new application points G'_H, G'_{LA} and G'_{RA} are computed from the initial points G_H, G_{LA} and G_{RA}.
In addition, s_x, s_y, s_z on one hand and m_x, m_y, m_z on the other hand represent different scaling factors to map the actual motion represented by the couple $(a(t), w(t))$ in the workspace of the different actuators. As previously described, those scaling factors are computed so as to use the workspace of each actuator in an optimal way. More precisely, computing the scaling factors m_x, m_y and m_z is one using a preprocessing step that consists of in finding the maximal amplitude f with respects to the values of $a(t)$ and $w(t)$ over the whole time interval. An exhaustive numerical analysis is thus performed to find the joint optimal discretized values m_x, m_y and m_z. Several solutions may be admissible in the parametric space and the one that offers the best isotropic behavior is selected.

4.3.3 *Output of the models*

A comparison of the outputs of the models is described in this section to highlight their main differences. The outputs of simple translations and then rotations are compared together.
A linear forward acceleration on the Z axis can be described by $a(t) = \{a_x(t) = 0, a_y(t) = 0, a_z(t) = t\}^t$ and $w(t) = \{w_x(t) = 0, w_y(t) = 0, w_z(t) = 0\}^t$. Such a movement is rendered in the same way by both models. All actuators are moving simultaneously along the Z-axis as if the user were being pushed forward. The same behavior is observed for the other translations on Y and X axes. In these cases, the user is pushed upward or pulled toward the left side.
Secondly self-rotations are tested. For instance a left rotation around the Y-axis can be described by $a(t) = \{a_x(t) = 0, a_y(t) = 0, a_z(t) = 0\}^t$ and $w(t) = \{w_x(t) = 0, w_y(t) = \frac{t^2}{2}, w_z(t) = 0\}^t$ (the angular acceleration $w'(t)$ is linear). In this case (see figure 3), the outputs of the models are different. With the *Physical Model* the user's hands are moving along the X-axis toward the center while the head is not moving. With the *Geometrical Model*, the right hand is going forward (Z-axis) and the left hand is going backward (Z-axis) while the head slightly moves to the right side (X-axis). The same behavior is observed for rotations on other axes: the *Physical Model* renders self-rotation by an attraction of each part of the body toward the center G and the *Geometrical Model* renders them with desynchronized movements.
A 6DoF movement that combines translations and rotations is thus managed differently by each model depending on the amount of rotations.

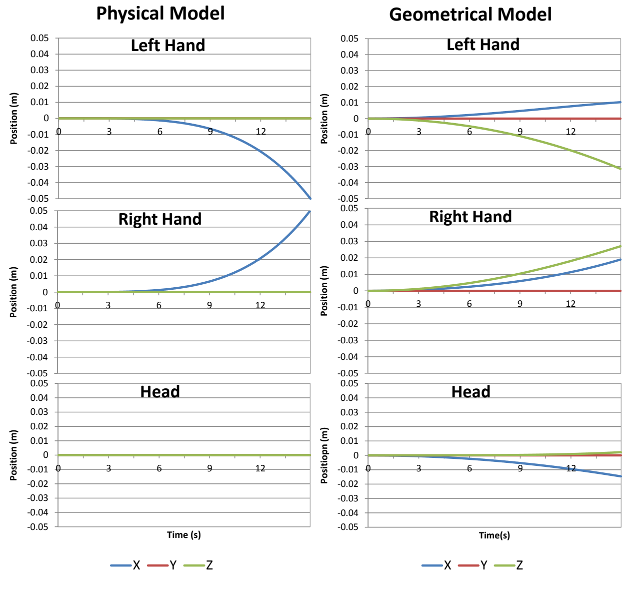

Figure 3: Output of the models (*Physical* on the left, *Geometrical* on the right) for a left rotation around Y-axis of 15 seconds. The position in meters is plotted for each actuator LA, RA and H, and for each axis.

4.4 Haptic Rendering

Whatever the model selected to control the chair, for each instant t of the simulation, each actuator A (namely H, LA

and RA) has to be in its targeted position G'_A (namely G'_H, G'_{LA} and G'_{RA}).
Most force-feedback devices (such as Novint Falcons) are impedance haptic devices, and the position of the actuator is thus not directly controllable. Indeed this kind of device is designed to sense the current position of the actuator and to provide a reaction force to the user. A classical spring-damper model may be used to control these devices in pseudo-position. The force F_A applied to an actuator A is computed by:

$$F_A = k(G'_A - P_A) - dV_A \tag{7}$$

where G'_A is the targeted position, P_A the current position of the actuator, V_A its velocity, k the spring constant and d the damping constant.

4.5 Provisional Conclusion

The models and the rendering algorithm were integrated to a home-made multimedia player that allowed the haptic rendering on three force-feedback devices to be synchronized with the audiovisual playback. The haptic loop runs at 1KHz and the value of the force F_A is updated at each instant t. The control software is written in C++ and runs on an ordinary personal computer.
Our initial tests showed that the force capabilities and workspaces of the Novint Falcons were sufficient to move the user's head and hands. Our system enables the experience of novel motion sensations when viewing virtual navigation (see figure 4).

Figure 4: The user, comfortably installed on our device, is experiencing passive navigation enhanced by a haptic effect of motion.

5. USER STUDY

A user study was conducted to evaluate the quality of the simulated motion and to quantify its impact on the user's perceived quality of experience (QoE).
17 participants took part in the study, aged from 21 to 54 ($\bar{x}$=36.11 σ_x=11.11). Five were female, two participants were left-handed and one already used a Novint Falcon device. The pilot study was presented as a single experiment lasting 20 to 30 minutes. Each participant was first introduced to the Novint Falcon and given a demonstration of its force capabilities. This step aimed to reduce the "surprise effect" for novice users. Participant was asked to passively experience each stimulus (see figure 4 and section 5.1) and then answer a questionnaire (see section 5.3).

5.1 Sequences: Haptic-Audiovisual Contents

Two driving sequences were created to test our device, and evaluate the sensation of motion and quality of experience (see figure 5). We generated two 1-minute videos and the associated descriptions of the global motion in terms of $a(t)$ and $w(t)$.
Our first sequence was a video of a **real car** driving session. Data was first captured using a front passenger equipped with a camera and an inertial measurement unit that sampled data at 30Hz.
The second sequence was a video of a **virtual car** racing video game. The main camera of the 3D simulation was placed inside the car in order to have a passenger point of view of the race. The visual output of the simulation was recorded while the accelerations and turn-rates of the car were extracted at 50Hz from the physics engine.

Figure 5: Haptic-Audiovisual contents. Left - Real video sequence of a car driving. Right - virtual car race.

5.2 Variables

To evaluate the quality of the simulated motion (and of the models) and the impact of this haptic feedback on the QoE, we defined four types of haptic feedback to be rendered with each sequence. **Physical Feedback**, computed from the physical model; **Geometrical Feedback** derived from the geometrical model; **No Haptic Feedback** in which only the audiovisual content was displayed, serving as a control to show how the other conditions impact on the QoE; and lastly **Random Haptic feedback** was provided. This random feedback was derived from low-pass filtered white noise (cutoff frequency $F_c = 0.5Hz$) played throughout the video. The amplitude of the signal was limited to the capabilities of the actuators. This last feedback was not synchronized to the video and was used to evaluate the effect of providing a continued haptic feedback.
All **height conditions** (two videos sequences x four types of haptic feedback) were presented in random order to the participants.

5.3 Measurement of QoE: questionnaire

A questionnaire was designed to evaluate the QoE of passive navigation enriched with haptic feedback. QoE relates to the subjective user experience with a service or an application [7]. This questionnaire was based on the four factors we wanted to evaluate [2]: realism, comfort, sensory and satisfaction. "Sensory" characterized how the haptic feedback contributed to the immersion. "Realism" describes the degree to which the simulation is realistic and consistent with the user's representation of the real world. This factor is particularly helpful in evaluating the quality of the simulated motion. "Comfort" measures how comfortable is the system. "Satisfaction" determines measures user enjoyment. Each factor was evaluated by questions rated on a 5-point scale. A mean was calculated for each factor. The sum of the scores gave a global QoE score. Table 1 presents the questions used to evaluate the QoE.

Factor	Question
Realism	How much did this experience seem consistent with your real-world experiences?
	How strong was your feeling of self-motion?
Sensory	How much did the haptic feedback contribute to the immersion?
	Were the haptic and visual feedback synchronized together?
Comfort	Was the system comfortable?
	How distracting was the control mechanism?
Satisfaction	How much did you enjoy using the system?

Table 1: QoE Qestionnaire. Each question is rated on a 5-point scale from 1 (Not at all) to 5 (Totally)

5.4 Results

Two hypothesis are tested: the *HapSeat* enhances the quality of experience and generates a sensation of motion. Shapiro-Wilk and Bartlett tests were performed on our data and the normality and homoscedasticity for most distributions could not be assumed. Hence non-parametric tests were used to analyze the results presented in this section.

As described above, a score for the four factors, realism, sensory, comfort and satisfaction were obtained using a questionnaire (see figure 6 and table 2). The main result confirms our first hypothesis. Our device significantly enhances the quality of experience (Friedman Anova: $p = 8.44e^{-08} < 0.05$). The Wilcoxon test with the Holm-Bonferroni correction has been used for the post-hoc analysis (see table 3). With the haptic feedback computed from the *Physical* or *Geometrical* model, the QoE is significantly higher than without haptic feedback ($p < 0.05$). However the QoE of the *Geometrical Model* is not significantly different from the QoE of the *Physical Model* ($QoE_G = 15 \approx QoE_P = 14.20, p = 0.5575 > 0.05$). It seems that haptic feedback consistent with the video is necessary to improve the QoE: user scores for random feedback are not statistically different to the no feedback condition ($QoE_N = 8.36 \approx QoE_R = 9.45, p = 0.4816 > 0.05$).

This tendency is observable for three factors. Presenting users with haptic feedback computed from our models resulted in significant increases in their reporting of Realism (Friedman Anova, $p = 3.80e^{-08} < 0.05$), Sensory (Friedman Anova, $p = 7.02e^{-08} < 0.05$) and Satisfaction (Friedman Anova, $p = 3.86e^{-07} < 0.05$) scores. However Comfort remained equal for all conditions: the Friedman Anova is significant, $p = 1.27e^{-03} < 0.05$, but Wilcoxon tests cannot confirm this hypothesis, $p > 0.05$ (see table 3).

Finally no significant differences are found for the QoE of each model between the two sequences *Real Car* and *Virtual Car* (Wilcoxon test, $p_{Geo} = 0.3933$ and $p_{Phy} = 0.4173 > 0.05$).

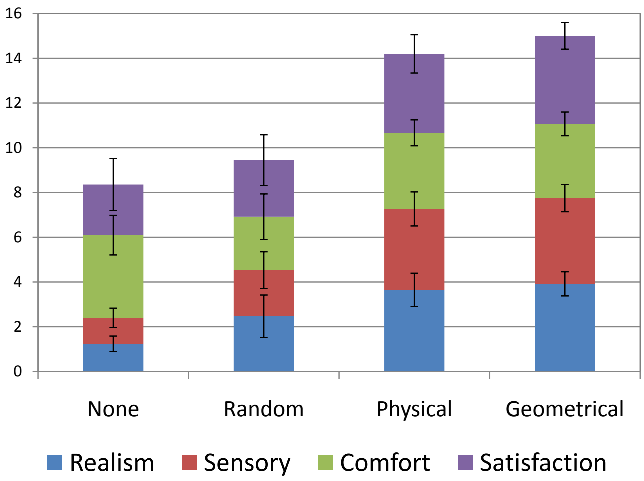

Figure 6: Quality of experience. The haptic feedback provided by the Physical and Geometrical models significantly improves the QoE.

Factor / Model	QoE	Realism	Sensory	Comfort	Satisfact.	
None	8.3578	1.2353	1.1618	3.6961	2.2647	$\bar{x}$
	2.0741	0.3477	0.4325	0.8853	1.1608	σ_x
Random	9.4479	2.4688	2.0625	2.3854	2.5313	$\bar{x}$
	2.9550	0.9481	0.8190	1.0187	1.1324	σ_x
Physical	14.1961	3.6471	3.6176	3.4020	3.5294	$\bar{x}$
	2.5521	0.7451	0.7609	0.5790	0.8564	σ_x
Geo.	15	3.9167	3.8333	3.3166	3.9333	$\bar{x}$
	1.7904	0.5401	0.6099	0.5300	0.5936	σ_x
F. Anova	35.7534	37.3958	36.1324	15.7554	32.6279	χ^2
	3	3	3	3	3	df
	$8.44e^{-8}$	$3.80e^{-8}$	$7.02e^{-8}$	$1.27e^{-3}$	$3.86e^{-7}$	p
	***	***	***	*	***	sig.

Table 2: Means ($\bar{x}$) and Standard deviations (σ_x) for each model with respects to each factor. A Friedman Anova ($\chi^2, df, p.value$) has been performed on each factor.

In order to evaluate the second hypothesis, the answers to the two questions of the Realism factor were analyzed (see figure 7, Q1 on top and Q2 on bottom and table 4). The results from Q1 suggest that the simulated motion was perceived as realistic (Friedman Anova $p = 3.60e^{-05} < 0.05$). A Wilcoxon test with the Holm-Bonferroni correction was also performed on our data (see table 5). Again, no statistical difference between the *Physical* and *Geometrical* models is observed ($Q1_P = 3.6 \approx Q1_G = 3.8$, $p = 0.6356 > 0.05$) but they are significantly different from the *Random* and *None* conditions ($p < 0.05$). The results from Q2 follow the same pattern. Both models provided a strong sensation of motion, significantly higher than *Random* and *None* conditions (Friedman Anova $p < 0.05$, Wilcoxon tests $p < 0.05$).

5.5 Discussion

Our results suggest that the *HapSeat* does enhance the user experience during passive navigation simulation. Both rendering models significantly increased the QoE compared to the Random and None feedback conditions. Our results also suggest that the synchronization of the haptic effect

QoE	Geometrical	None	Physical
None	$1.5e^{-05}$	-	-
Physical	0.5575	$6.5e^{-05}$	-
Random	$6.9e^{-05}$	0.4816	0.005
Realism	Geometrical	None	Physical
None	$5.3e^{-06}$	-	-
Physical	0.4336	$4.1e^{-06}$	-
Random	0.0005	0.0004	0.0028
Sensory	Geometrical	None	Physical
None	$5.5e^{-06}$	-	-
Physical	0.5169	$5.2e^{-06}$	-
Random	$4.6e^{-05}$	0.0004	0.0002
Comfort	Geometrical	None	Physical
None	0.1575	-	-
Physical	0.4927	0.1664	-
Random	0.0161	0.0064	0.0107
Satisfaction	Geometrical	None	Physical
None	0.002	-	-
Physical	0.4992	0.0095	-
Random	0.0037	0.4992	0.0273

Table 3: Pairwise comparison of each model for each factor using Wilcoxon test with Holm-Bonferroni correction.

Question **Model**	Q1	Q2	
None	1.2647	1.2059	$\bar{x}$
	0.5338	0.3976	σ_x
Random	2.1563	2.7813	$\bar{x}$
	0.9259	1.0483	σ_x
Physical	3.5588	3.7353	$\bar{x}$
	0.7045	0.8860	σ_x
Geometrical	3.8	4.0333	$\bar{x}$
	0.5606	0.6935	σ_x
F. Anova	20.4615	12.86	χ^2
	2	2	df
	3.60^{-05}	$1.61e^{-03}$	p
	***	*	sig.

Table 4: Means ($\bar{x}$) and Standard deviations (σ_x) for each model with respects to Q1 and Q2. A Friedman Anova ($\chi^2, df, p.value$) has been performed on each question.

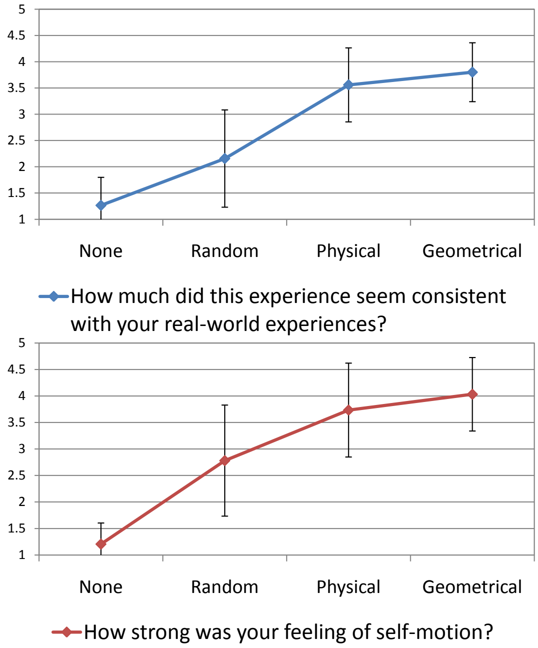

Figure 7: Realism factor details. Users found the simulation realistic (top) and experienced a stronger sensation of self-motion (bottom).

Q1	Geometrical	None	Physical
None	$4.5e^{-06}$	-	-
Physical	0.6356	$3.9e^{-06}$	-
Random	0.0002	0.0030	0.0005
Q2	Geometrical	None	Physical
None	$3.5e^{-06}$	-	-
Physical	0.3743	$3.5e^{-06}$	-
Random	0.0045	0.0001	0.0238

Table 5: Pairwise comparison of each model for both question using Wilcoxon tests with the Holm-Bonferroni correction.

with the visual content is important.

In this study, no statistical differences are found between the models. This is probably due to the nature of the simulation (car driving) which does not fully exploit the 6DoF. Only translation (car acceleration) and rotation (turns) were included in the two sequence tested. More complex content, such as a plane or spaceship flight or a rollercoaster ride, might produce results that highlight differences between the models. In addition, the parameters of the models could be tuned to increase their differences. Each one is composed of several factors which impact the use of the workspace. The *Physical Model* could be also improved by modeling the segments and joints of the user's skeleton instead of treating the user as a single rigid body.

We observed that the simulated motion was not perceived in the same way by all participants. Some of them found that the haptic feedback computed from our models was reversed. For instance, they expected to be pushed backward instead of being pulled forward when the car (real or virtual) was moving straight forward. However this observation was not consistent among all users. Some participants expected to feel the reaction force instead of the acceleration only during turns, but found the feedback acceptable for linear translations, i.e. when the car was going straight forward. Though some participants seem to prefer a reversed force feedback in specific cases, this does not mean that the output of the models should necessarily be reversed. One might posit two user profiles "direct" and "reversed" to address this, it can certainly be said that the design of the associated haptic feedback is not straightforward. The perception of motion simulated by force-feedback devices require further evaluation. Studies are also needed to understand the influence of a haptic stimulus on the perception of a visual stimulus.

Our the device was reported as comfortable and user friendly. The perception of comfort was similar with and without haptic feedback, suggesting that no extra discomfort is introduced by the system. Nevertheless comfort could be improved, especially for the headrest. Some participants reported that the haptic feedback for the *real car* sequence contained too much vibration. This may be explained by the greater sensitivity of proximal joints to movement than distal joints [6]. Similar displacements are perceived more strongly on the head than on the hands. If this vibration that contribute to realism when perceived by the user's hand, might be too intense for the head. So far the haptic rendering for all actuators is the same. But dedicated algorithms could be implemented for each device. As a minimum, a low-pass filter could be applied on the output of the actuator H to reduce vibration.

6. CONCLUSION & PERSPECTIVES

We have presented the *HapSeat*, a novel approach to the simulation of 6DoF effect of motion. Instead of moving the whole user's body as it is traditionally done with motion platforms, we stimulate only parts of the body. Our hypothesis was that, coupled with a visual stimulus, these local stimulations could trigger a sensation of motion and thus improve the quality of experience.

Results of a user study show that the two control models, *Physical* and *Geometrical*, succeed at enhancing the quality of experience during passive navigation. Furthermore participants reported having experienced a realistic sensation of self-motion.

Future work to improve of the models and study of the user's perception of the simulated motion is planned. The prototype could be extended by adding more points of stimulation, for instance, for the legs. The input capabilities of the devices could be used to allow the user to interact with the simulation, offering the prospect of extending applications of the *HapSeat* to flight or driving simulators, teleoperation, etc.

To conclude, this original approach yields a new way to simulate a sensation of motion in a consumer environment and allows the creation of more immersive applications.

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